A Preliminary Analysis of the Risks to the Balmorhea Springs Complex Posed by Unconventional Oil & Gas Development

INCLUDING SAN SOLOMON SPRINGS AT BALMORHEA STATE PARK

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Report available at earthworksaction.org/BalmorheaAnalysis

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Contents

Summary

A large regional flow system combined with local recharge supports groundwater discharge from the Balmorhea Springs complex, including San Solomon Springs at Balmorhea State Park.

The regional flow system begins south of the Davis Mountains but flows northwest to near the Delaware Mountains where it curves southeast and flows back to the spring complex. Faults control the flow system by forcing groundwater to the surface through natural pathways from underlying bedrock aquifers to the surface or to shallow alluvial aquifers. Alluvial aquifers consist of soil and rock particles through which groundwater flow through pores around the particles and bedrock aquifers are solid rock through which groundwater flows primarily through fractures. The underlying bedrock aquifers are up to a couple thousand feet deep. Local recharge into shallow alluvial aquifers mostly from runoff from the Davis Mountains also supports the spring discharge, causing significant flow increases and decreasing the natural baseflow salinity. Due to irrigation development in the area, the current average spring flow is about 33,000 acre-feet/year (af/y), down from about 38,000 af/y about 80 years ago.

Unconventional oil and gas development could occur in geologic formations consisting of shale or very fine sand from 10,000 to 12,000 feet beneath the ground surface. This development could negatively affect water quality of the Balmorhea Springs primarily by leaks from well bores affecting the deep groundwater flow pathways within several miles of the springs. Fluids, both gas and liquids, could reach shallow aquifers that feed the springs. Long-term (greater than ten years) risks to the springs occur from hydraulic fracturing within the general area, which could be estimated as far as five to ten miles from the springs due to the potential long-term horizontal transport from the formations developed for oil and gas through faults to the surface These risks are not quantifiable but the probability that contamination will occur is significant. Surface spills would likely impact the springs at some point in the future if development occurs very near the springs along pathways through which contaminants could flow to the springs. Water use that occurs anywhere along the flow path supporting the springs could decrease the spring flows in addition to that expected due to planned development. An increase in hydraulic fracturing near the springs could increase the frequency of earthquakes which could impact water quality at the springs, as occurred in 1931, or affect groundwater flows by disrupting the pathways from the bedrock to the spring discharge point.

The shallower target formations near and southwest of the springs are not as desirable for oil and gas development as they are further north within Reeves County because of their heterogeneity. Recent acquisitions in deeper formations suggest that there will be at least additional exploratory development near Balmorhea.

Introduction

The oil & gas industry has targeted various formations near Balmorhea, TX for unconventional oil and gas development involving hydraulic fracturing (fracking). The increase in drilling permits for Reeves County exemplifies this trend (Figure 1). Approximately 34 wells have spudded recently near Balmorhea, TX (although the source does not define "recently") (Figure 2). These wells have caused concerns about how the development of unconventional oil and gas expected for the Delaware Basin portion of the Permian Basin of west Texas (Howard Weil 2014) could impact the Balmorhea Springs.

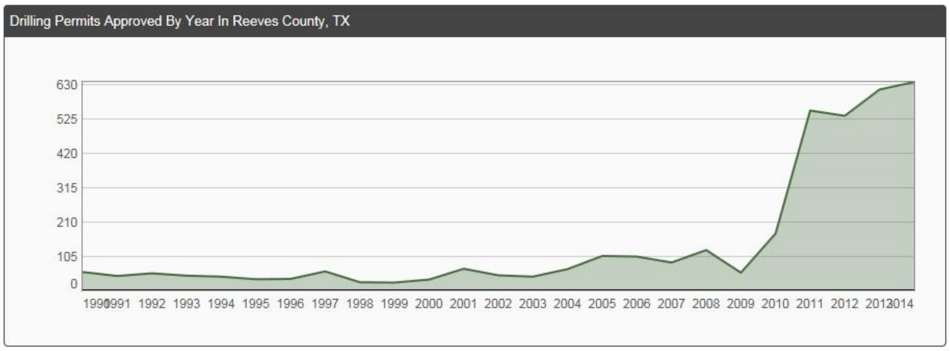

Figure 1: Drilling permits approved by year in Reeves County, TX, source http://www.texas-drilling.com/reeves-county/drilling-permits, accessed 9/3/16.

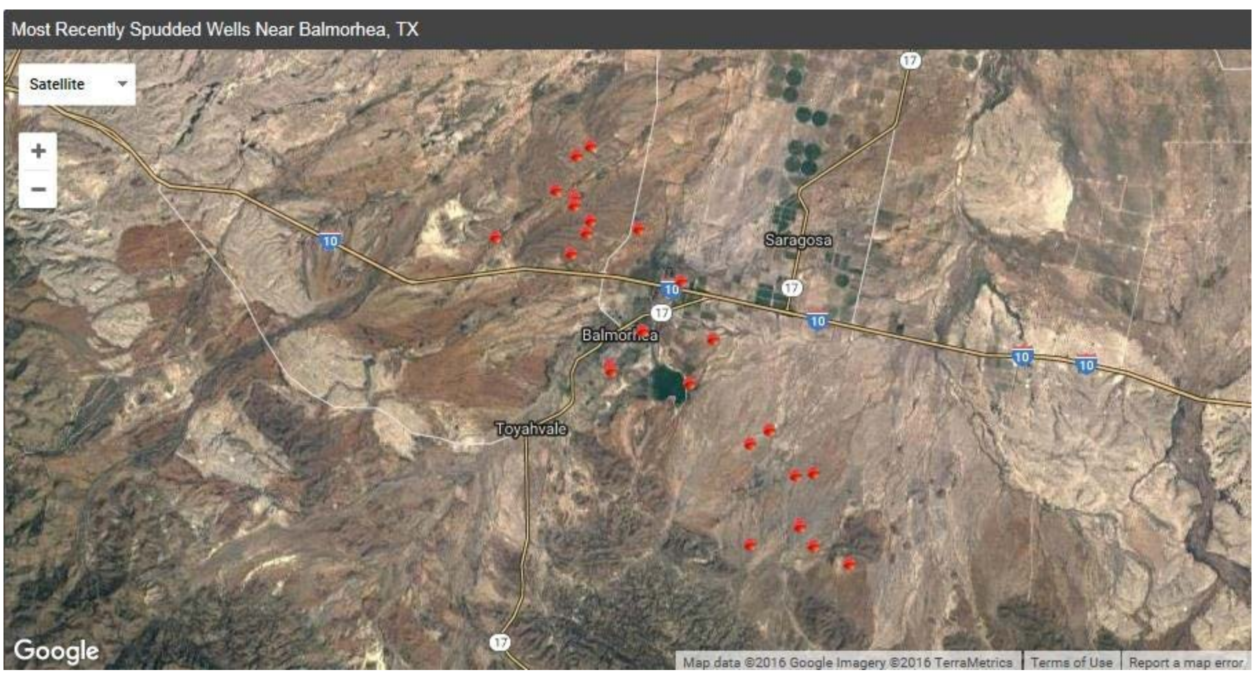

Figure 2: Aerial view showing general layout of "recently" spudded wells near Balmorhea. Source http://www.texas-drilling.com/reeves-county/balmorhea accessed 10/3/16.

This project involves a preliminary risk assessment of the impacts oil and gas development could have on the Balmorhea Springs complex. The springs are referred to as a complex because there are several springs along a geologic transect from the Davis Mountains south of Balmorhea northeast toward the Pecos River (TWDB 2005) (Figure 3). The focus is on San Solomon Springs that discharges at Balmorhea State Park but also relevant to other springs in the complex such as Phantom Lake Spring to East Sandia Spring (Figure 1). Comanche Springs and others lie further east possibly on the same transect (Figure 2). All of the springs are important, as well, because their flows provide endangered species habitat for the Comanche Springs Pupfish (USFWS 2013).

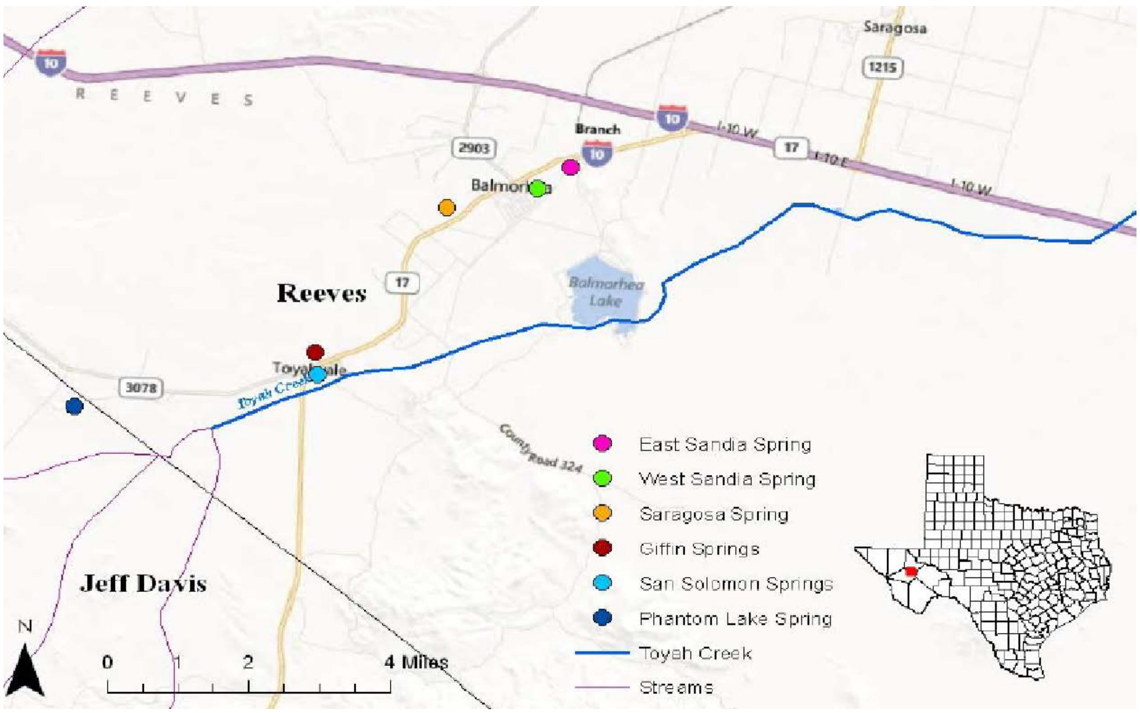

Figure 3: Site map snapshotted from USFWS (2013).

RISKS TO THE SPRINGS

1) The potential for fracking fluid, flowback, or produced water to migrate through pathways between the target formation and the sources of the springs;

2) The potential for leaks of fluids, including gas, from the well bores into shallower aquifers more closely connected to the springs;

3) The potential for spills or leaks from fluid impoundments into shallow aquifers closely connected to spring pathways;

4) The potential for fracking to affect spring flow rates by affecting flow in the spring sources. Fracking can change pathways which could change the artesian pressure and hence the spring flow rate.

5) The effect of pumping groundwater for fracking to reduce spring flow.

These risks would be in addition to risks caused by other development, which cannot be assessed in detail here. For example, projected groundwater development west of the springs would likely cause a drawdown and intercept sufficient groundwater flow over the next 50 years to substantially divert a large amount of the flow to the springs (USFWS 2012, p 23).

An assessment of the risks to the springs from fracking development in the deeper basin near the springs requires an understanding of the combination of hydrogeology at the springs and in the deeper Delaware Basin, specifically the formations newly targeted for fracking near Balmorhea. This memorandum uses literature review and flow system analysis to develop a conceptual flow and transport model (CFTM) for both the springs and the Delaware Basin:

- Literature review of the hydrogeology of the springs, regional flow systems, and basin and reservoir hydrogeology for the Delaware Basin, as part of the Permian basin.
- Conceptual model of the connections between target formations and the springs. This includes both groundwater flow and contaminant transport.
- Describe current and proposed oil and gas development in the basin based on industry literature and considering well and development logs for nearby springs.
- Assess risk to springs due to contaminant transport to the springs or flow interruption by oil and gas development and the conceptual model of the basin.

This paper also researches similar situations where fracking has impacted springs or shallow aquifers.

HYDROGEOLOGY OF THE BALMORHEA SPRINGS AREA

Balmorhea Springs lies in the southwest portion of Reeves County (Figure 4) near the boundary with Jeff Davis County. It is about three miles southwest of Balmorhea (Figure 5) and two miles from the Jeff Davis county line. Phantom Lake Spring, although not shown, lies just over the county line into Jeff Davis County three miles from Balmorhea Springs. The springs have been developed into a pool in the Balmorhea State Park (Figure 6). Reeves County lies within the Delaware Basin portion of the Permian Basin (Figure 7). There are at least seven springs in the Balmorhea area (Figure 3).

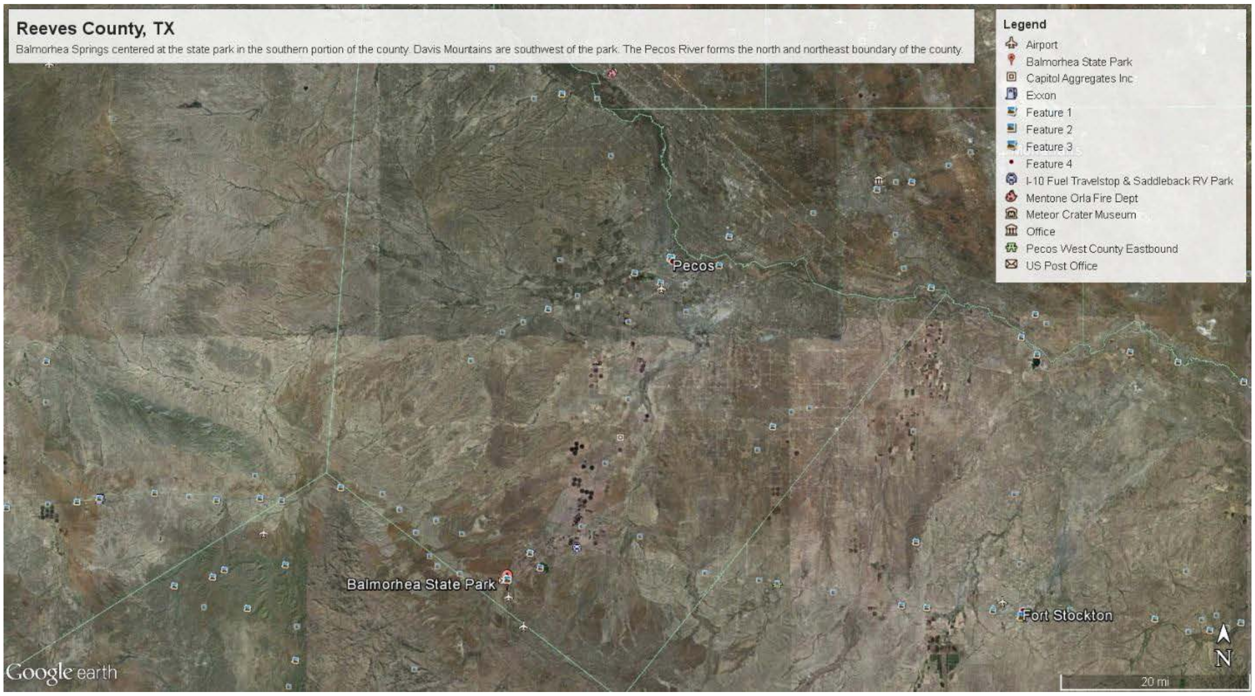

Figure 4: Aerial view from 2014 showing Reeves County, TX.

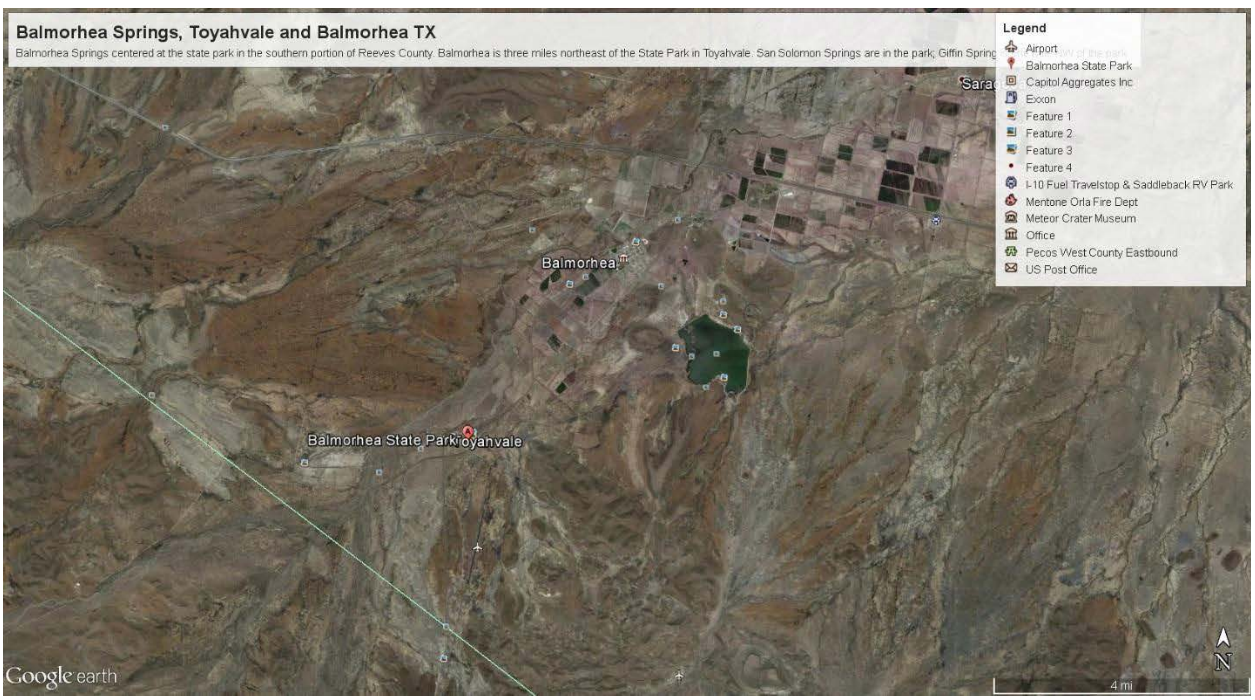

Figure 5: Aerial view from 2014 showing close-up of Balmorhea State Park, Toyahvale, and Balmorhea, TX.

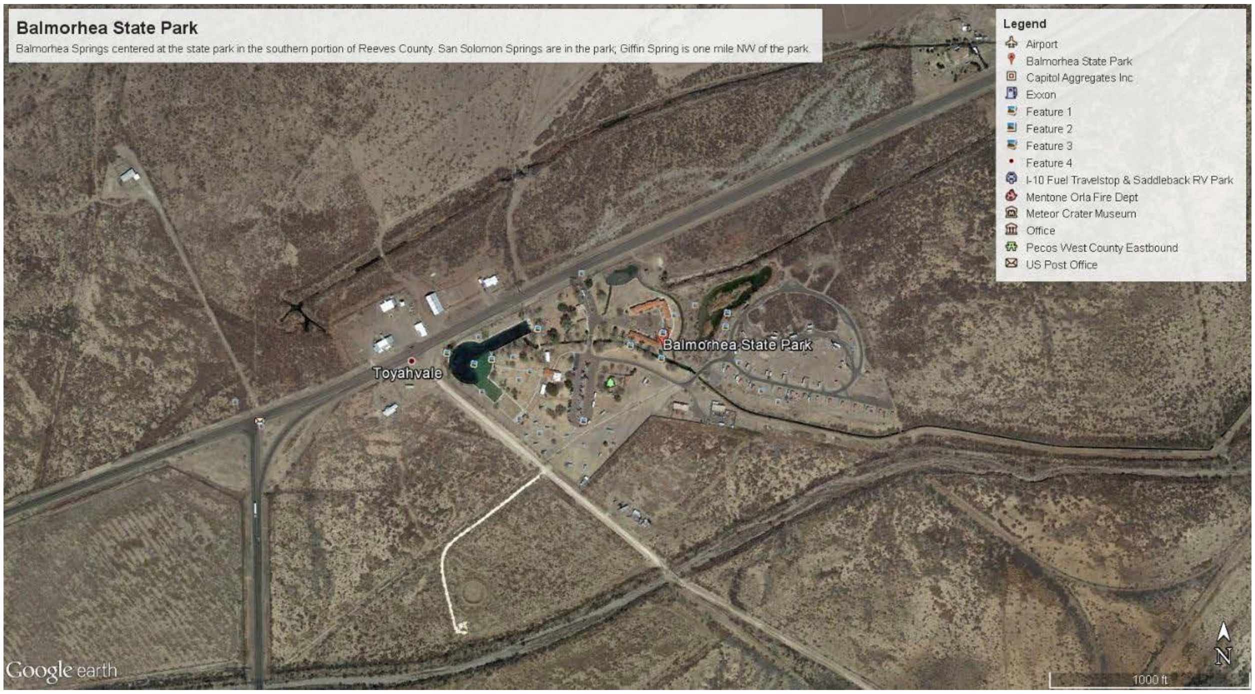

Figure 6: Aerial view from 2014 showing the Balmorhea State Park and the ponds and canals within the park. Although not identified, Giffin Srings may be the head of the canal about 1000 feet NW of the main pond at the state park.

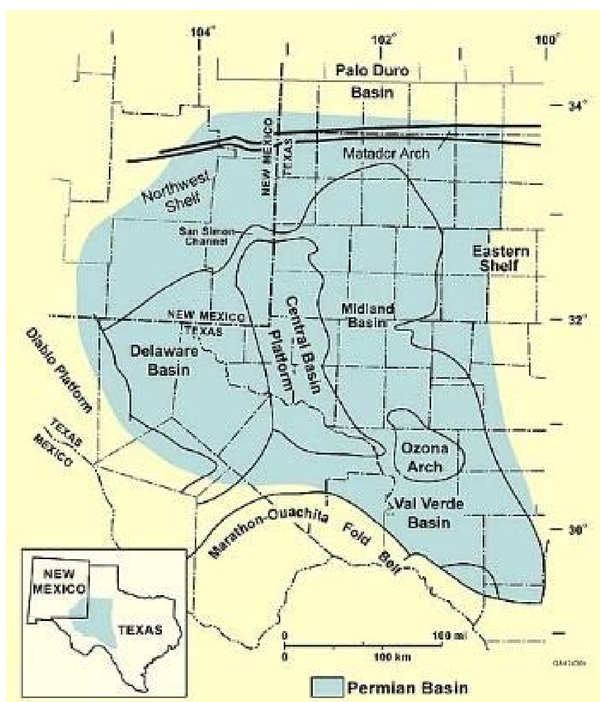

Figure 7: General outline of the Permian Basin. Reeves County lies to the right and below the Delaware Basin label. Source: https://en.wikipedia.org/wiki/Permian_Basin_(North_America), accessed 10/4/16.

Spring Flow

The San Solomon Springs makes up the primary flow for the pool at the Balmorhea Springs State Park (Figure 6). Flows from that spring have dropped somewhat over the years and currently average from 25 to 30 cubic feet per second (cfs), although the flow can be somewhat variable (Figure 8). During field work completed in the early 1930s, the flow was consistently about 10 cfs higher, with separate independent measurements of baseflow at 37.7, 37.6, and 38.0 cfs (White et al 1941, p 99).

Phantom Lake Spring, described as "once the largest spring in Jeff Davis County", lies west and upgradient of San Solomon Spring. Its flow had been decreasing since irrigation began in the 1940s (Figure 9). White et al (1941, p 99) reported flows from 10 to 114 cfs; the only flows that have occurred since about 2000 have been in response to heavy rainfall events because perennial flow ceased at that time. Because there is currently no natural outflow due to pumping having lowered the groundwater below the level required for there to be discharge, Phantom Lake Spring flow is maintained with pumps (USFWS 2013, p 18). This means that water is pumped from surrounding groundwater and used in place of the previous spring flow. TWP (2005, p 24) documented a fall in groundwater level near the springs of about a foot between May 2001 and July 2003, thereby documenting that lowering groundwater levels directly causes the springs to dry.

Giffin Spring, just 1.0 mile west from San Solomon Springs (Figures 5 and 6), reportedly has a constant 3 to 4 cfs although the USFWS (2013, p 14) stated it is not monitored due to being on private property However, TWP (2005) published a hydrograph showing relatively constant flows since about 1956 (Figure 8). White et al (1941, p 99) reported flows from 2.9 to 7 cfs.

East Sandia Spring apparently has flow but USFWS does not provide flow rate measurements (2013, p 15). Leon Springs, 40 miles east of Balmorhea, flowed at 18 cfs in the 1930s but ceased flowing in the 1950s due to irrigation pumping (USFWS 2013, p 18). Comanche Springs, in Fort Stockton, ceased flowing in 1961 (Id.). Other springs in the Toyah basin, including Alamo, Irving, Buck, Hoban, Weinacht, Santa Isabel, and Splittgarber, went dry at approximately the same time (Id.). Saragosa Spring dried in the 1970s (USFWS 2013, p 19). White et al (1941, p 120) estimated flow from Saragosa Spring and the Toyal Creek springs to be about 9 to 10 cfs, or 6500 to 7000 af/y.

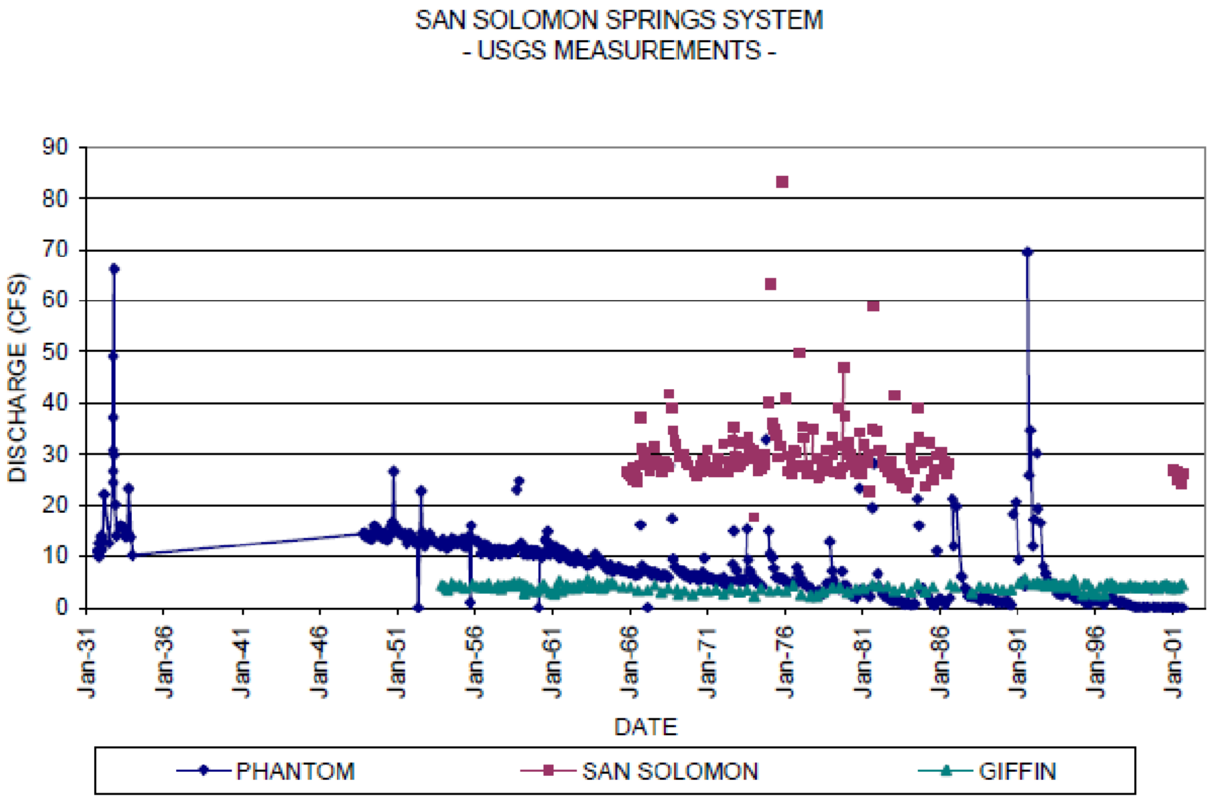

Figure 8: Figure 69 from TWP (2005) showing flows since 1931 for three springs in the Balmorhea area.

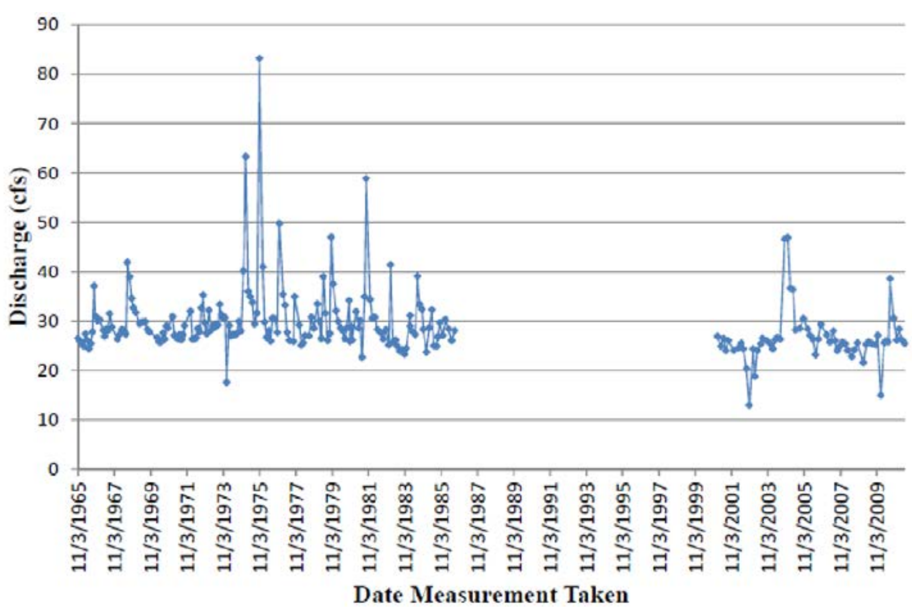

Figure 9: Figure 9 from USFWS (2013) showing flows measured at San Solomon Springs.

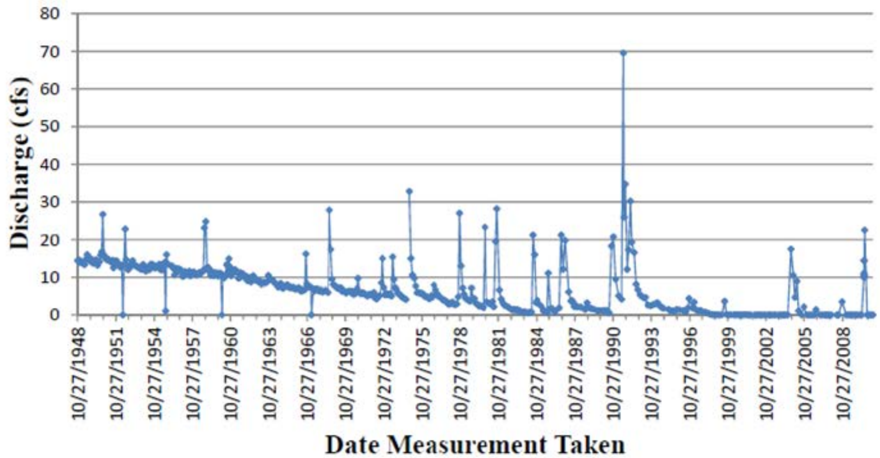

Figure 10: Figure 5 from USFWS (2013) showing flows at the Phantom Lake Spring.

Most sources attribute the declines to irrigation pumping (Sharp 2001), although drought may also contribute. TWP (2005, p 109) minimized the role of pumping, especially at Phantom Lake Spring, and suggested that there could have been cementation or alteration of flow paths due to an earthquake[1], an increase in Phreatophytes that remove flow from the flow path leading to the springs, or a reduction in recharge due to long-term drought or climate patterns.

White et al (1941, p 99) observed that Phantom Lake Spring and San Solomon Spring increase soon after a significant rainfall, as may be verified on Figures 8 through 10. They noted that the flow at Phantom Lake Spring increases faster than further downgradient. Flow from Phantom Lake Spring increases approximately 24 hours after a significant recharge event while it takes about 48 hours for the flow to increase at San Solomon and Giffin Springs (TWP 2005, p 79).

Total dissolved solids (TDS) from the regional springs was around 2000 to 2300 mg/l, but it decreased significantly during storm events. White et al (1941, p 100) even noted that "water of the springs has rather a high mineral content, but it becomes quite fresh during periods of peak discharge". White et al (1941, p 101) reported three measurements for each of Phantom Lake Spring, San Solomon Spring, and Giffin Spring regarding TDS during normal and high flow conditions in 1930 and 1932. TDS decreased almost 90% at Phantom Lake Spring and about 75% at the other two springs. In 2011, San Solomon, Santa Rosa, Comanche, and Diamond Y Springs discharged groundwater with specific conductance equal to 2430, 6100, 3570, and 6730 uS/cm, respectively (Bumgarner et al. 2012).

[1] Sellards (1932) documented the 1931 earthquake near Valentine, Texas, and reported observations of San Solomon Springs becoming muddy due to and remaining so three days after the earthquake.

Regional Flow Paths

White et al (1941) used TDS and mineralization data of the groundwater to suggest that the Balmorhea Springs "are fed from an extensive system of solution channels in Lower Cretaceous limestone, that constitute in the aggregate a very large reservoir" (p 119). White et al suggested that most of the flow originated in the Davis Mountains, south of the Balmorhea Springs System (Figure 5). Significant drops in TDS during rainfall events indicates a significant mixing with new recharge, especially at Phantom Lake Spring. Most of the springs discharge from surficial gravel which could be connected to shallow systems which provide the short-term recharge.

Age-dating that suggests the average age for baseflow from the springs ranges from 10,000 to 16,000 years old but also that storm events contribute much younger water of local origin (Chowdhury et al 2004, p 341). Other geochemical observations shows a difference in TDS and isotopes that indicates the groundwater from wells in the Davis Mountains differs substantially from the Balmorhea Springs system. Geochemical analysis has shown that waters originated to west of the Apache Mountains in the Salt Basin and south of the Davis Mountains (Uliana et al. 2007). Ratios of Na to Cl show that much of the water originates from bedrock aquifers discharging into shallow aquifers. The depth of the aquifers, described in the following subsections, is up to a 1000 feet but not as deep as the oil and gas producing formations.

The consensus is the spring system is a primary discharge point from a long regional flow system (USFWS 2013, Uliana et al. 2007, Sharp et al 2003, Sharp 2001) that originates in Ryan Flat southwest of the Davis Mountains; the system flows northwest through Lobo and Wild Horse Flat to Apache Mountains where it turns eastward through preferential flow conduits and then southeast and south into the Toyah Basin where structural controls force the spring discharge (pathway 7 in Figure 11). The regional flow path is inflow to the Edwards-Trinity aquifer (Bumgarner et al. 2012), as simulated in a numerical model of that aquifer (Clark et al. 2014). The geochemistry of the groundwater flow confirms the regional flow path but also supports the idea that springflow is a combination of regional flow with local recharge (Bumgarner et al. 2012, Uliana et al 2007). Specifically, runoff recharging at the base of the Davis Mountains likely causes the short-term flow increases at Phantom Lake and San Solomon Springs.

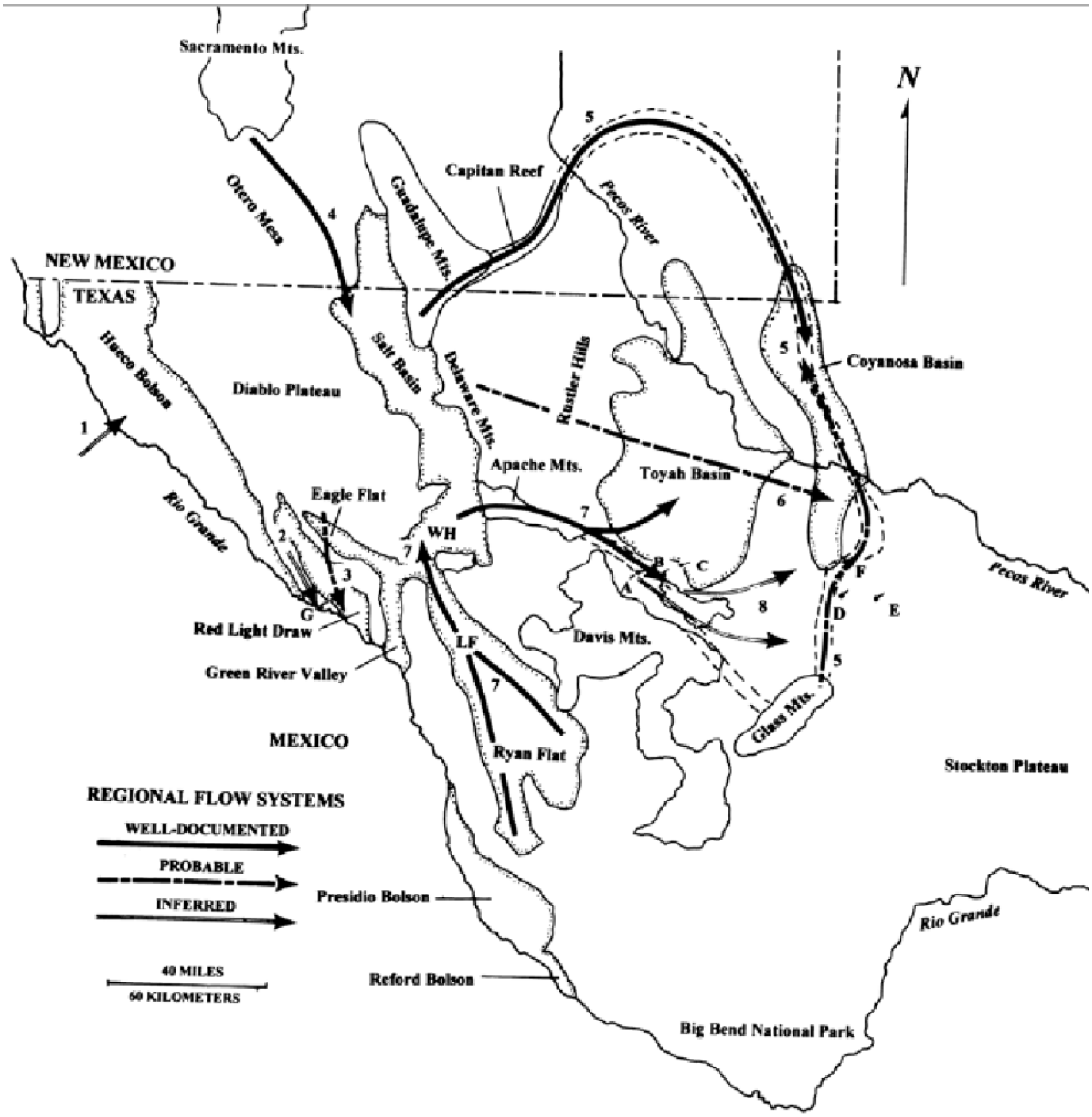

Figure 11: Regional flow systems for West Texas snapshotted from USFWS (2013). WH and LF denote Wild Horse Flat and Lobo Flat, respectively. Springs: A, Phantom Lake Spring, B – San Solomon and Giffin Springs, C East and West Sandia Springs, D, Leon Springs, E, Comanche Springs, F, Diamond-Y Springs, and G, Indian Hot Springs and is the regional flow system that feeds Balmorhea Springs (A, B, and C), or the Salt Basin-Toyah Basin-Pecos River system; see USFWS (2013) for a definition of the flow systems numbered 1 – 6.

A coarse cross-section representative of a portion of the pathway may be found in Richey et al (1985) (Figures 12 and 13), which show a geologic section from ground surface to the Wolfcamp Formation. The figure shows the general outline and dip although the section is across the north end of Reeves County (Figures 12 and 13). As will be discussed below, the Wolfcamp and Bone Spring Formations are the target formations for oil and gas development; their properties are discussed below. Both the Wolfcamp and Bone Spring formation subcrop into Cenozoic alluvium where both are likely recharged. The scale of the figure is coarse, but it appears the water level at the updip end of the formation would be several hundred feet higher than the ground surface near the Balmorhea Springs. This suggests that mountains on the edge of the Delaware Basin could be a source of groundwater in the deep formations beneath those directly sourcing the springs. It also causes an upward gradient from depth into the Rustler formation and Santa Rosa sandstone which form some of the aquifers near Balmorhea.

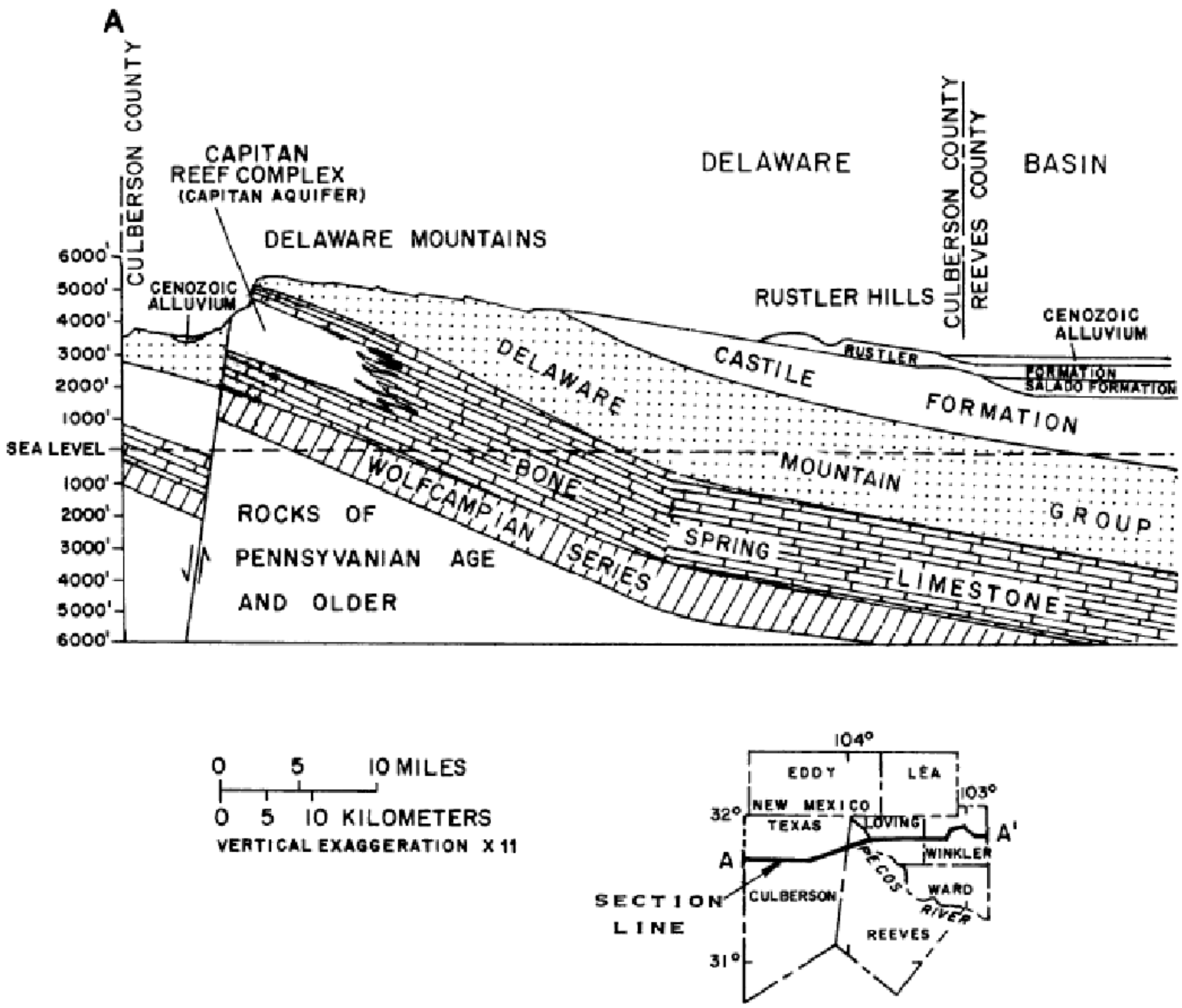

Figure 12: Geologic section across the Delaware Basin, from Richey et al (1985), Figure 2.

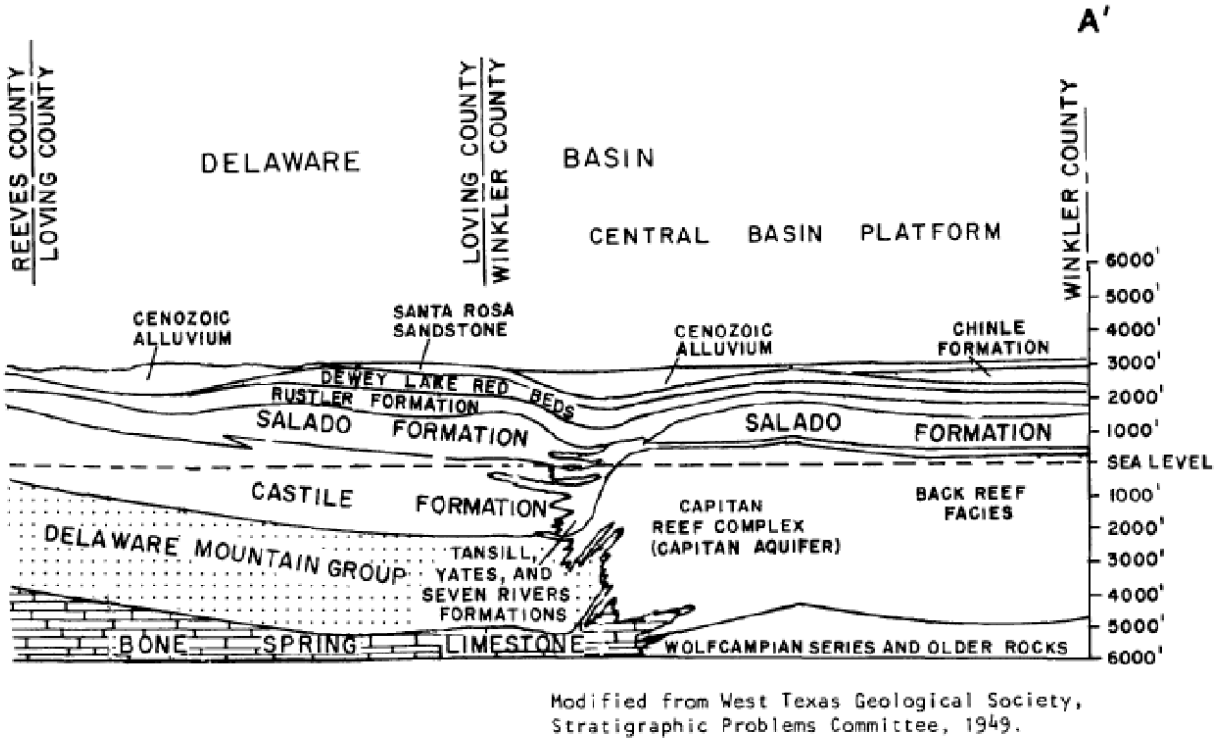

Figure 13: Figure 12, continued.

Combined flow as inflow to the Toyal Basin recently averaged about 33,000 af/y (TPW 2005, p 108). This contrasts with the flow reported from the early 1930s for Phantom Lake, San Solomon, Giffin, and East and West Sandia Springs which totaled 53, 104, and 65 cfs during three observation periods (White et al 1941), or 38,370, 75,290, 47,060 af/y. Discounting the higher values because they occurred likely during runoff events, the total flow from the spring system has decreased about 5000 af/y since the early 1930s. Adding observations from Saragosa and the Toyal Creek springs, total discharge from the flow system averaged about 55,000 af/y in the early 1930s.

Recharge to the Edwards-Trinity aquifer near the springs is from four sources (Bumgarner et al 2012, p 43):

1) Regional flow from the northwest. The authors identify this pathway as being from Uliana et al. (2007), but the original source does not mention the aquifer.
2) Runoff from nearby mountains that percolates into the gravels and alluvium
3) Irrigation return flow
4) Upwelling of deeper groundwater

Within the Edwards-Trinity, only water receiving mountain front recharge or irrigation return flow is less than 60 years old, based on tritium isotope testing (Bumgarner et al. 2012, p 43).

Geochemical evidence shows that relatively dilute with respect to TDS groundwater from mountains to the south influences the higher-salinity groundwater in the Edwards-Trinity aquifer (Bumgarner et al. 2012, p 45). The high salinity water can be linked to higher salinity groundwater in the underlying Rustler or Capitan formations (Id.). Additionally, the groundwater levels in the underlying formations are as much as

100 feet higher than in the Edwards—Trinity, a factor which provide the upward gradient needed to drive flow into the higher aquifer and the springs. Uliana et al. (2007) had linked higher salinity flow from the springs to dissolution along the pathway (Figure 11) from the northwest and initially from the south but did not assign it to formations.

Geology of the Spring System

The spring system is mostly fault-controlled, as may be seen in the geologic cross-section shown in Figures 14 through 16. Near the springs, the shallow formations slope upward in a southwest to northeastward direction (Figure 15). Bumgarner et al (2012, p 45) indicated that the Edwards-Trinity aquifer discharges through springs, including San Solomon, Santa Rosa, Comanche, and Diamond Y Springs, along fault zones. Downgradient flow through the bedrock (Figures 12 and 13) encounters the updipping layers that are offset by faulting (Figure 15) which can focus flow to discharge to the ground surface at the springs. The section in Figure 15 is only several hundred feet thick but implies that faulting reaches to depth beneath the springs.

Flow systems from west to east (Figure 11) may be partially blocked due to structural offsets (Bumgarner et al 2012) (Figure 16). The primary aquifer in the area, the Edwards-Trinity, has offsets that may prevent long distance flow along the aquifer. In section FB01 (Figure 16), three aquifer units are offset such as they are likely strong flow impediments. The plan view (Figure 16) shows extensive faulting in the Delaware Basin, with the Pecos Trough being a graben due to evaporate dissolution and surface caving (during Permian time). These structural offsets and faults among aquifers (Figure 16) facilitate vertical groundwater flow. The observed vertical gradient helps to drive the flow. Groundwater mounds observed along the Monument Draw trough east of the springs also reflect the upward gradient from depth (Bumgarner et al. 2012).

The springs, in the southwest portion of the county, are on the edge of the Delaware Basin where the basin depth is rapidly changing (Figure 17). As discussed in the next section, the depth to the Bone Springs formation is around 10,000 feet but it becomes significantly shallower to the southwest; in its north portion, depth approaches 20,000 feet. This would suggest the west to east dip observer to the north may occur in a southwest to northeast direction from the basin bounds in the Davis Mountains. The effect this has on the springs is unclear.

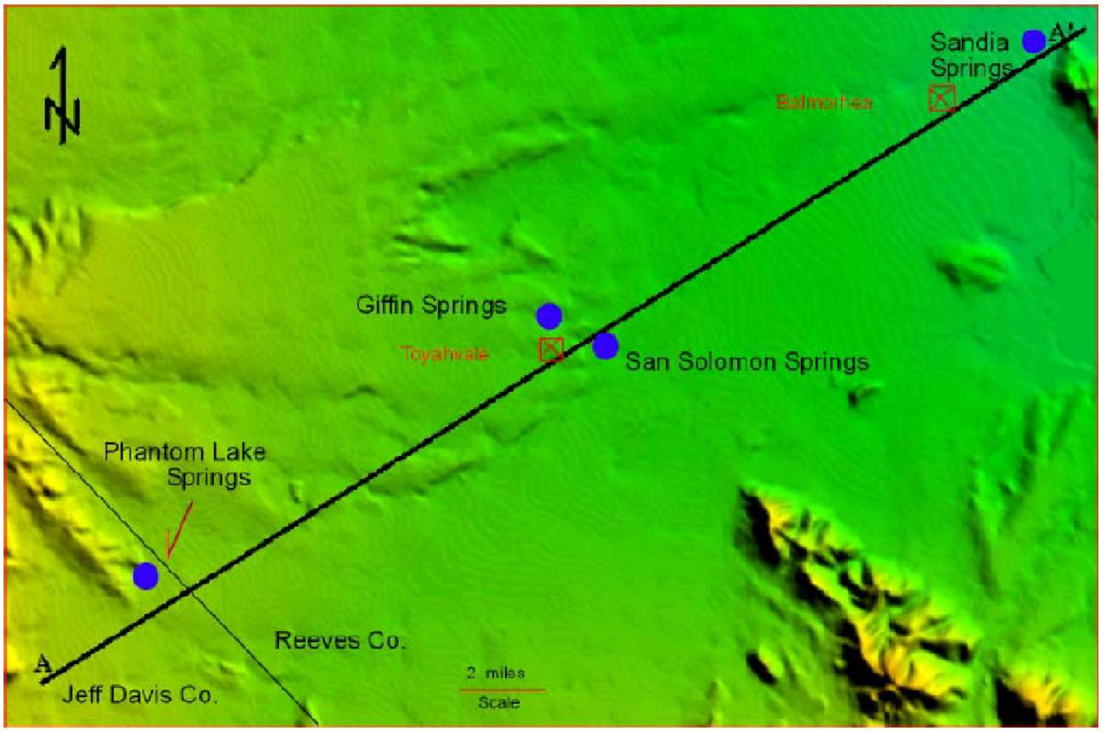

Figure 14: Figure 48 from TWP (2005) showing location of geologic cross-section shown in Figure 15.

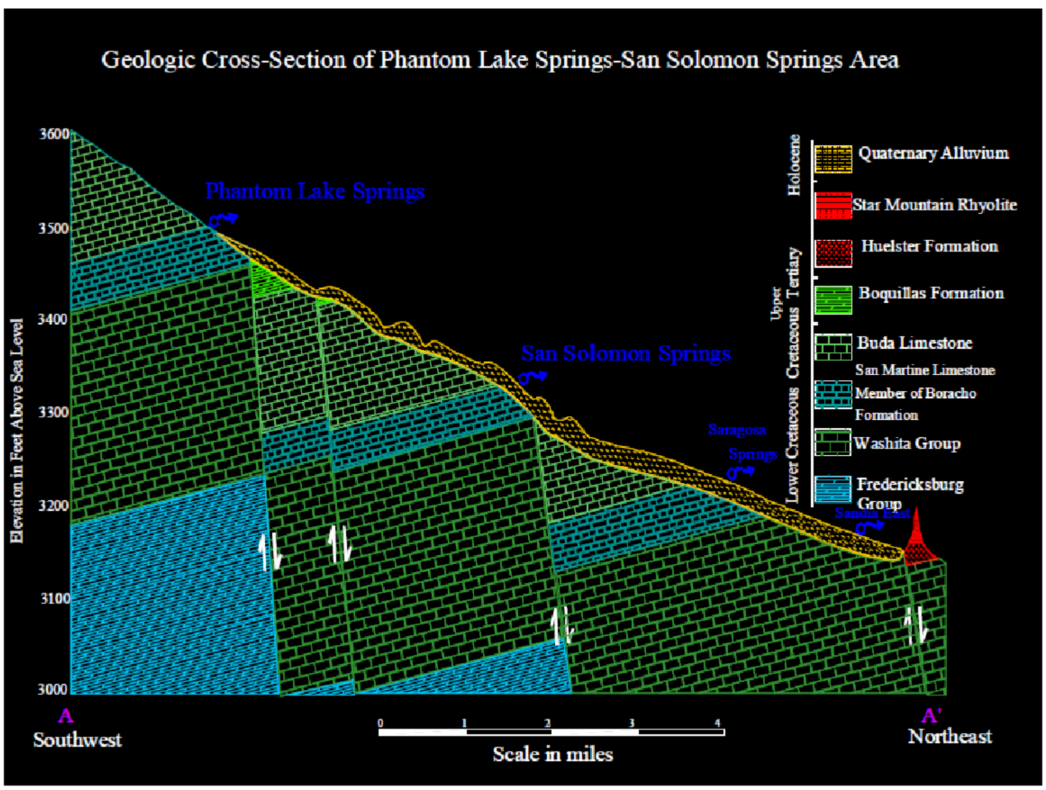

Figure 15: Figure 49 from TWP (2005) showing geologic cross-section from Phantom Lake Springs through San Solomon Springs.

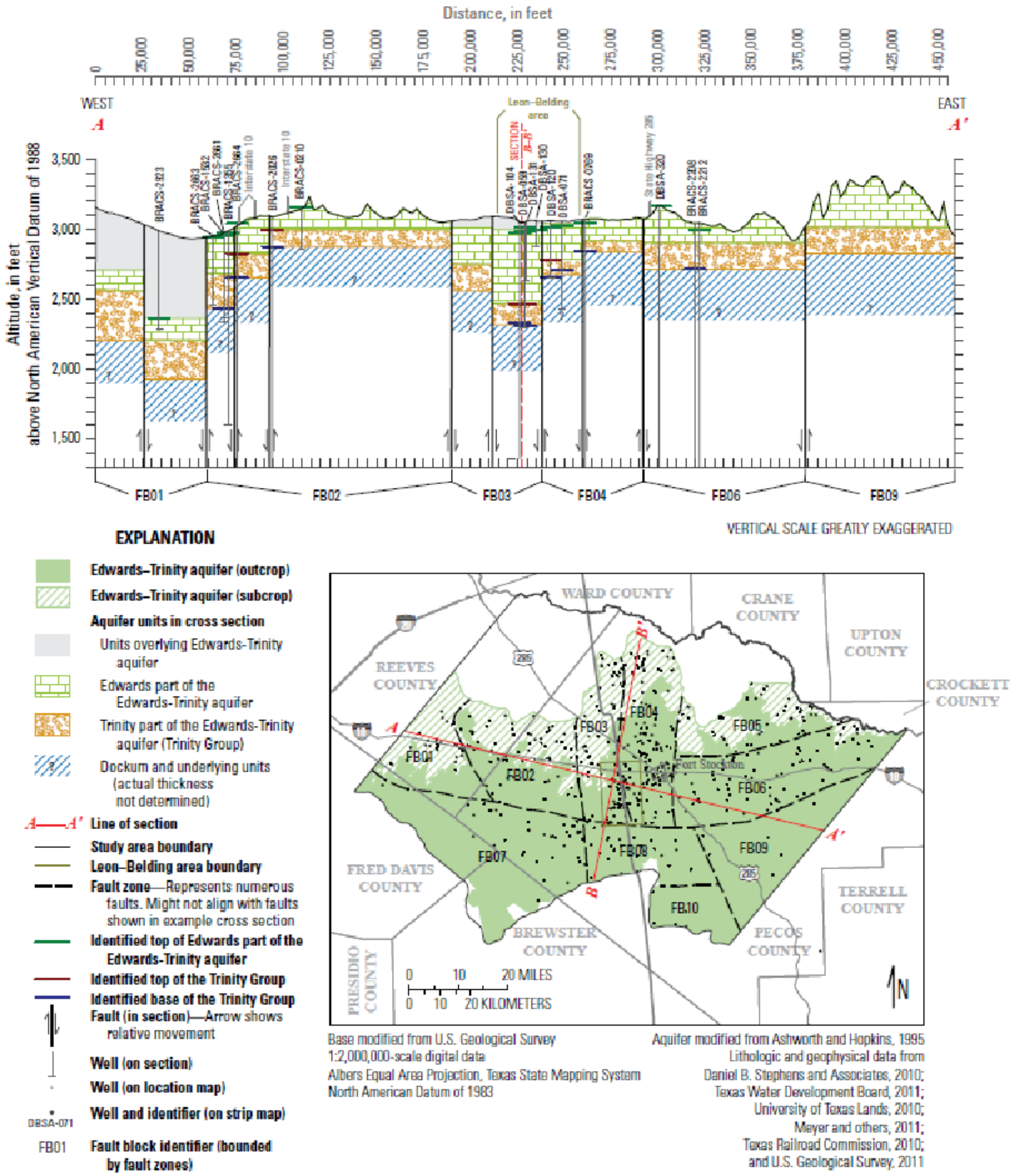

Figure 16: Figure 17 from Bumgarner et al (20120 showing structural offsets between aquifer units. Balmorhea Springs are within the FB01 area. The solid and hatched green are the Edwards-Trinity aquifer, outcrop and subcrop, respectively.

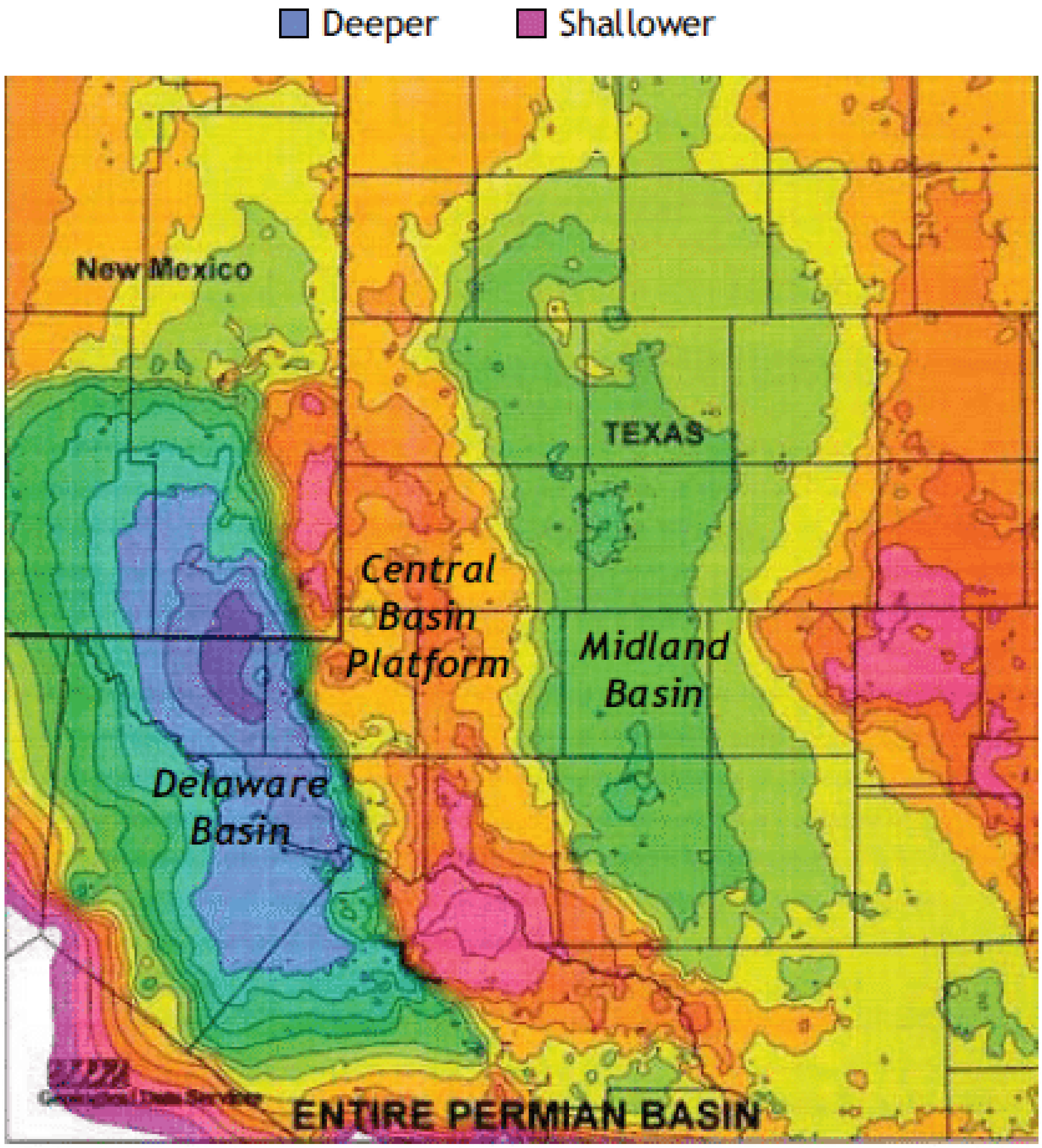

Figure 17: Map of Permian Basin showing relative depth. Reeves County is in the southwest portion of the map (see Figure 4 for general shape). Balmorhea Springs would lie between the green depth and the county boundary. http://info.drillinginfo.com/midland-basin-vs-delaware-basin/, accessed 10/3/16.

Oil and Gas Development

Recent interest in oil and gas development in the Delaware Basin, specifically in Reeves County southwest of Pecos, focuses on the Bone Springs Formation or the Wolfcamp Formation (Howard Weil 2014). The Avalon is a portion of the Bone Springs Formation. The most recent wells spudded in the area lie on a line that trends northwest to southeast through Balmorhea, about three miles northeast of the state park (Figure 2). According to listings (http://www.texas-drilling.com/reeves-county/balmorhea, accessed 10/3/16), most of those new wells were dry holes[2]; however, Howard Weil (2014, p 5) believes that development of the Bone Spring formation will expand successfully west and south of the Pecos River. Apache Corp has shown very recent interest the Alpine High region of the Delaware Basin (Figure 18) (http://www.ogj.com/articles/2016/09/ihs-markit-apache-s-alpine-high-discovery-in-historically-underperforming-area.html, accessed 10/10/16). Apache's focus includes the Pennsylvanian, Barnett and Woodford formations (http://www.naturalgasintel.com/articles/107668-apache-gushes-on-immense-discovery-in-permians-southern-delaware, accessed 10/10/16) which are lower than the Bone Springs or Wolfcamp. Clark (2016) indicates the five formations are an up-to-5000 foot thick package of oil and gas producing formations. Previously considered too geologically complex or containing too much clay (http://www.wsj.com/articles/apache-has-high-hopes-for-new-oil-field-discovery-in-texas-1473245702, accessed 10/10/16), some claim the Alpine High could be the largest energy discovery of the past decade (Id.).

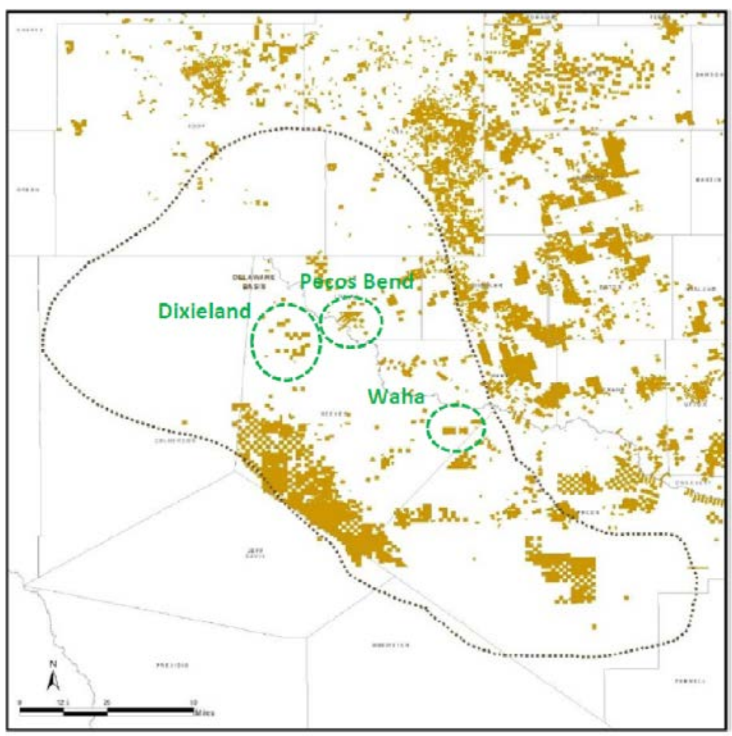

Figure 18: Apache Corp leases in Southwest Reeves County centered on the Alpine High with Balmorhea in the center (Clark 2016).

[2] Mapping on the Texas Railroad Commission website also verifies the dry holes near Balmorhea http://wwwgisp.rrc.state.tx.us/GISViewer2/, accessed 10/10/16.

The target formations (for unconventional oil and gas development) in the southern portion of the Delaware Basin, including Balmorhea Springs, are 3rd Bone Springs and the underlying Wolfcamp formation. The Bone Springs formation ranges from 2500 to 3500 feet thick, with the formation becoming thicker and deeper from west to east until it disappears at the Central Basin Platform (Howard Weil 2014, p 5). The Bone Springs formation varies between carbonate and sand with interbedded dark and carbonaceous shaly siltstones that are a barrier to vertical flow (http://info.drillinginfo.com/permian-basin-geology-midland-vs-delaware-basins/, accessed 10/3/16). The depth of the top of the Bone Springs formation is highly variable throughout the basin and is about 9000 to 10,000 feet near Balmorhea Springs (Figure 18). The Bone Spring formation throughout the Delaware Basin is very heterogeneous which has prevented operators from completing their horizontal wells for more than 4500 feet (Howard Weil 2014, p 7). This is half as long (and more expensive per length) as is common in the Midland Basin just to the north. The Wolfcamp formation lies beneath the Bone Springs and is about 2000 feet thick, but locally up to 6000 feet thick (Id.). The general lithology is interbedded shale and limestone (Id.). No additional lithology is available on the deeper formations because exploration has just commenced (Clark 2016).

Fairhurst et al (2012) indicate the Wolfcamp is the better target for southwest Reeves County and provide a map showing the boundary almost coinciding with the county boundary, meaning the edge is beneath the Balmorhea Springs (Fairhurst et al 2012, p 37). Produced water at high volume, up to 1200 barrels per day, was a problem for the Wolfcamp (Fairhurst et al. 2012, p 20). The formation is significantly overpressured (Fairhust et al. 2012, p 40), which can cause an upward gradient for groundwater flow.

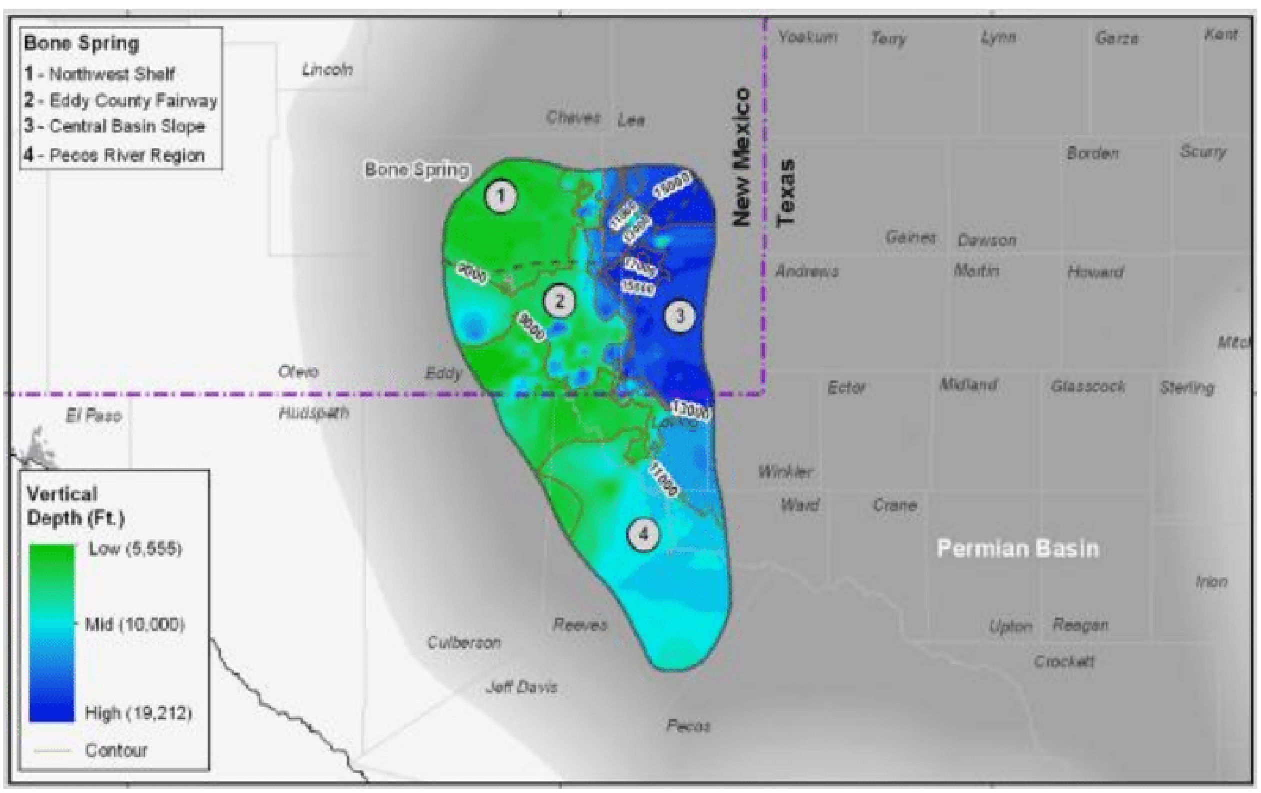

Figure 19: Depth to the top of the Bone Springs Formation. Source: http://info.drillinginfo.com/wp-content/uploads/2014/12/Permian-Figure-4.png, accessed 10/3/16. Based on Howard Weil (2014).

Potential Risks to the Balmorhea Springs from Oil and Gas Development

Oil and gas development could occur in the area of the flow system supporting the springs, meaning that oil and gas wells could be drilled through the aquifers that support the springs. That is a flow system that is supported by a long regional flow path with groundwater upwelling from depth to be the primary baseflow at the springs. Local groundwater recharge quickly reaches the springs after a storm event as evidenced by the occasional spikes in the flow hydrographs from the springs. Spring flow therefore is connected to both deep and shallow groundwater flow.

Oil and gas development presents four apparent risks to the springs. The following subsections consider the potential for each of those risks.

The potential for fracking fluid, flowback, or produced water to migrate through pathways between the formation being developed for oil and gas and the sources of the springs

Fracking would occur in formations that are very deep, over 10,000 feet, below the springs. However, faults could provide a pathway that connect the target formations to shallow groundwater (the faults are generally described in the Geology of the Spring System section above). It therefore is possible that upward gradients enhanced by fracking pressures could cause fluids to reach shallow groundwater as studied in other formations. Recent model studies have estimated that fluids could flow from similar shale layers in similar sedimentary basins, to shallow aquifers by following natural pathways such as faults and that the flow could be enhanced by hydraulic fracturing to occur in less than 10,000 years depending on assumed conditions (Chesnauw et al. 2013; Gassiat et al. 2013; Kissinger et al. 2013; Myers 2012).

Myers (2012) found that transport from the Marcellus to shallow aquifers could occur over a period from 10 to more than a thousand years, depending on the conductivity assumed to result from fracking -- his model had the horizontal gas well intersecting a vertical fault connecting the shale to the near-surface. Gassiat et al. (2013) modeled a high permeability, continuous, 10-m wide fault zone from the shale to the shallow groundwater with hydraulic fracturing simulated as a change in permeability over a 2-km long, 150-m thick zone. Kissinger et al. (2013) simulated a continuous 30-m thick vertical fault with a vertical head drop of up to 60 m to vertically drive a plume of hydraulic fracturing fluid introduced into the lower aquifer. After 30 years under this scenario, simulated hydraulic fracturing fluid had reached the shallow aquifer with the injected concentration reduced by a factor of 4000. Lateral migration of contaminants occurred at rates up to 25 m/y (Lange et al. 2013). Chesnauw et al. (2013) modeled flow along a fracture pathway between a target shale zone and surface aquifer in a two-dimensional framework, 3000-m long by 3000-m deep and 1 m thick. A key factor in all of the modeling studies is that they utilized generic stratigraphic and topographic cross-sections with idealized formation properties. All of the models found the most rapid transport could occur through a vertical fault system. Another key fact is that although they considered flow through a fault, they likely underestimated the potential for preferential flow through small but highly permeable fractures even within a preferential flow zone. These studies are all applicable to the Permian Basin.

Although none of these studies focused on the Permian Basin, the pathways described would be similar and if there is a force to drive fluids to the surface, these model studies are relevant to the hydrogeology

near the Balmorhea Springs. As described in the Hydrogeology section, the flow systems supporting the Balmorhea Springs are fault controlled. If those faults are conductive there is a potential for fracking fluids or produced waters released from the target formation to reach shallow groundwater and affect the springs. Model results discussed above are based on conditions that would allow transport of liquids to occur due to hydraulic fracturing within a few hundred years for some of the conditions they simulated. Released gas could reach shallow aquifers very quickly due to buoyancy and liquids would take from ten to thousands of years depending on many factors which are unknown about these faults.

There is no way to quantify this risk because of the lack of knowledge of the properties and the fact that this type of pathway has never been verified to transport fracking fluid; however, transport of formation water from similar depths to the surface has been documented in other areas, such as the Marcellus (Llewellyn 2014). The transport time from the point of contamination to the springs could range to hundreds of years, depending on the hydraulic properties of the pathway, as found in the modeling studies discussed above.

The potential for leaks of fluids, including gas, from the wellbores into shallower aquifers more closely connected to the springs

Fracking can also release fluids underground from the wellbore along pathways that can reach shallow aquifers or bedrock aquifers near the surface that support the springs, thereby shortcutting some of the transport times discussed in the previous subsection.

Many studies have highlighted the increase in CH_4 concentration in water wells within one kilometer of fracked wells, with the CH_4 being identified as thermogenic -- meaning it was sourced from deep formations (Darrah et al. 2014; Jackson et al. 2013; Osborn et al. 2011). If it will affect shallow wells, it would also affect the springs. Others have noted the presence of increased CH_4 in water wells in valley locations along faults and lineaments (Molofsky et al. 2013; Fountain and Jacobi 2000) which is similar to the fault pathways present near Balmorhea. Darrah et al. (2014) listed scenarios that can lead to higher methane concentrations in shallow groundwater, based on studies in Texas and Pennsylvania, including:

1) in situ microbial methane production;
2) natural in situ presence or tectonically driven migration over geological time of gas-rich brine from an underlying source formation or gas-bearing formation of intermediate depth (e.g., Lock Haven/Catskill Fm. Or Strawn Fm.);
3) exsolution of hydrocarbon gas already present in shallow aquifers following scenario 1 or 2, driven by vibrations or water level fluctuations from drilling activities;
4) leakage from the target or intermediate-depth formations through a poorly cemented well annulus;
5) leakage from the target formation through faulty well casings (e.g., poorly joined or corroded casings);
6) migration of hydrocarbon gas from the target or overlying formations along natural deformation features (e.g., faults, joints, or fractures) or those initiated by drilling (e.g., faults or fractures created, reopened, or intersected by drilling or hydraulic fracturing activities);
7) migration of target or intermediate-depth gases through abandoned or legacy wells

Scenarios one and two are not anthropogenic, but fracking could enhance the second scenario (Gassiat et al. 2013; Myers 2012). Warner et al. (2012) and Llewellyn (2014) provide evidence for the type of brine movement discussed in scenario two. The upward flow into the Edwards-Trinity aquifer could also be enhanced. Drilling or vibrations caused by fracking can release dissolved gas or change its transport through shallow groundwater so that it affects shallow aquifers and therefore the springs and water wells that discharge from those springs.

The third scenario is a mechanism by which fracking releases gas into shallow groundwater through which it can flow significant distances. The long pathways leading to the Balmorhea Springs could allow gases that reach the shallow aquifer to reach the springs.

The fourth and fifth scenario describes the potential movement of gas from depth along the well, due to faulty construction, to shallow groundwater. This would be a source to the Balmorhea springs if there are wells near the springs.

The sixth scenario is the movement of gas from the target formation through natural pathways, such as faults or fractures, to shallow groundwater. Other studies have documented the rate at which gas released by hydraulic fracturing can move through the groundwater. Gas tracers released during hydraulic fracturing were found at production wells 750 feet away from the source within days (Hammock et al 2014). They also found evidence of gas migration to a sandstone layer 3000 feet above the Marcellus shale. A model study based on conditions found at the southwest Pennsylvania site used in Hammock et al. estimated that gas can flow from a well bore leak through a sandstone rock matrix to a well 170 m away in times ranging from 89 days to 17 years depending on conditions (Zhang et al 2014). The southwestern Pennsylvania site is similar to the Permian Basin because both were formed during geologic periods of sedimentation which led to extensive layers of sedimentary rock in which oil and gas developed. Darrah et al. (2014) found several gas wells within one kilometer of fracked wells in the Barnett shale region of Texas that experienced large increases in gas concentration between annual sampling events which suggests that gas transport of up to a kilometer occurred in a time period of less than a year.

Where there are abandoned wells, scenario seven is an obvious potential scenario, although it includes transport through bedrock to the abandoned well. There are abandoned wells in the Balmorhea area that could provide another pathway (a survey of abandoned wells is beyond the scope of this work). Regardless of the mechanism causing methane to reach shallow groundwater, either as dissolved or buoyant gas, it can flow to nearby wells, streams and springs.

The Balmorhea Springs flow through pathways that would be very conducive to transporting fluids if introduced to those pathways; both the conductance and upward gradient appears to be present at the springs. Gas would also flow upward due to buoyancy.

Based on previous studies (Fontenot et al 2013, Osborn et al 2011) which show a high proportion of shallow wells within a short distance of oil and gas wells being impacted by gas or metals, there appears to be a greater than 50% chance that contaminants would affect the pathways reaching the spring. However, these sources are usually short-lived, so the impacts would be temporary. The magnitude of the impacts could be low because the high volume of the flow could dilute the contaminants.

The potential for spills or leaks from fluid impoundments into shallow aquifers closely connected to spring pathways

Contamination can reach shallow groundwater near a gas well by percolating through the unsaturated zone. The potential for spills or leaks to follow such a path is clear, but there is little specific research.

In a substantial review paper concerning the impact of shale gas on regional water quality (Vidic et al. 2013), the authors cited just one report from grey literature (Considine et al. 2012) regarding spills and one journal article from the early 1980s regarding spills transporting through shallow groundwater (Harrison 1983).

Gross et al (2013) documented 77 spills that included BTEX compounds (benzene, toluene, ethylbenzene, and xylene) in Weld County, Colorado between July 1, 2010 and 2011. A large proportion of the spills reached groundwater and caused concentrations to exceed groundwater quality standards, but the concentrations dropped off steeply with distance from the spills. The spill size ranged from 1 to 177 barrels (up to 7400 gallons).

Rahm (2011) surveyed fracking in Texas but found no documented instances of groundwater contamination from spills or other fracking sources. Fontenot et al (2013) found that TDS, arsenic, strontium, selenium, and barium were higher in drinking water wells in active gas drilling areas in the Barnett Shale of Texas. However, they suggest this was due to vibrations releasing metals or changes in groundwater levels changing pH which could change the adsorption ability of the aquifer thereby releasing some of the metal. Methanol and ethanol was also higher near gas wells which could be due to methanol released from well bores or shallow biotic activity.

Produced water disposal will be a potential contaminant source, with TDS approaching 200,000 mg/l and naturally occurring radioactive material near 10,000 picocuries/L (Kharaka et al. 2013) in addition to potential fracking fluid additives.

Similar spills and pathways could affect the Balmorhea Springs. A spill that reaches shallow groundwater that feeds the springs would affect at least temporarily those springs. However, during baseflow most of the groundwater discharge from the springs is from deep sources and it is unlikely that a surface spill would contaminate deep flow paths. Even if a spill occurs in the recharge zone for the long flow paths (Figure 11), BTEX would likely adsorb to soil before it reaches the springs.

The potential for contamination from surface spills affecting the springs is several percent per year for sources within a couple miles upgradient of the springs, especially if those sources are unlined or do not follow appropriate management practices. Surface spills from further away or downgradient are unlikely to affect the springs.

The potential for fracking to affect spring flow rates by affecting flow in the spring sources.

One hypothesis is that fracking can change pathways which could change the artesian pressure and hence the spring flow rate. Based on the ratio of TDS in the springs to that in the formation, at most 1/100th of the spring water could be sourced from the Bone Springs or Woodcamp formations, or below, that are being developed. Because of the multiple shale layers and the need for more extensive fault connections to connect deeper layers, it is more likely that deep-formation groundwater reaching the shallow aquifers

would be from the higher formations. Therefore, it is unlikely that fracking would affect the flow due to impacts in the formations. However, it is possible that seismicity associated with fracking could change the flow paths from depth to the shallow groundwater, as noted by TWP (2005).

A more likely impact of unconventional oil and gas development would result from water use if water for fracking is withdrawn from groundwater wells that feed the springs.

Nicot and Scanlon (2012) reported that water use for shale gas production in Texas is less than 1% of all water use, but that impacts vary greatly by area. Scanlon et al (2014b) reported that well development in the Texas Eagle Ford gas play equaled 16% of the water use in that area. Water use in the Permian Basin doubled between 2008 and 2010 (Scanlon et al 2014a). Localized water development for oil and gas would amplify current ongoing drawdown predicted to occur due to groundwater development (TWP 2005).

Scanlon et al (2014a) reported that oil wells within the Permian Basin have required an average 800,000 gallons to develop; that amount was in the lower half of the basins surveyed. An interesting result was that developing unconventional oil wells uses much less water than do unconventional gas wells (Scanlon et al 2014a, Table 1).

The potential for induced earthquakes to affect flow in the springs

Sellards (1932) described how a 6.0 earthquake affected turbidity in the San Solomon Spring for up to three days after the event. Earthquakes could affect the flow pathways that support the springs, by causing the fractures to become geologically offset so that a flow pathway ends or whether particles move and fill the fracture pathway so that flows decrease. Either of these factors could cause the groundwater to discharge elsewhere. Frohlich et al. (2016) documented that earthquakes exceeding magnitude 3.0 have increased from 2 to 12 events per year since 2008 due to deep wastewater injection. Due to the increased development near Balmorhea Springs, there is a significant possibility for an earthquake near the springs that could affect the flow pathways to the spring.

Conclusion and Recommendations

Unconventional oil and gas development could affect the Balmorhea Springs primarily by leaks from well bores affecting the deep pathways within a couple miles of the springs.

Long-term (greater than ten years) risks to the springs occur from fracking within the general area, which could be estimated as five to ten miles from the springs due to the potential long-term horizontal transport. These impacts are not quantifiable but there is a significant probability that the springs would be impacted at some point in the future.

Surface spills would likely impact the springs at some point in the future but only if development occurs near and on a pathway to the springs.

Water use that occurs anywhere along the flow path supporting the springs could decrease the spring flows in addition to the amount the flows will decrease due to current and planned development. The time for the decrease to occur depends on the distance the development is from the springs.

Neither well development nor surface containment of hazardous materials or production water should be allowed within an area upgradient of the springs if contaminants could reach the springs.

The depth of the target formations becomes shallower as one moves to the southwest due to the steep gradient of the top of the Bone Springs formation (Figure 18). The changing depth is due to the basin formation processes which leads to significant faulting. Howard Weil (2014) describes the formation as "heterogeneous" in general.

All of these factors lead to low-producing wells because the formation is not sufficiently homogeneous to produce oil or gas for large areas necessary for profitable development. The Apache Corporation, Forest Oil, Quicksilver, and Royal Dutch Shell hold acreage near the Balmorhea State Park, and that is on the edge of their holdings (Howard Weil 2014, Figures 54, 73, 85, and 89, respectively). However, as noted above, Apache Corp has recently shown substantial interest in other formations in the Alpine High, which is centered on Balmorhea. It is therefore likely there will at least be some development for testing in the immediate Balmorhea area, although the target formations are very deep and below other low permeability formations, including some which have been targeted in the past.

To prepare for potential development, the springs should be sampled and monitoring begun for the following chemicals. Nearby wells should also be sampled for the same items.

- Dissolved methane, ethane, and propane: these samples would allow an assessment of the current state within the springs. If there is substantial methane, it would indicate there is a source affecting the springs without oil and gas development. If ethane and propane are also high, it would indicate that the source is deeper and likely thermogenic.
- TDS, arsenic, selenium, strontium: Fracking has been shown to cause these to increase either due to vibrations or due to pH changes. If TDS changes significantly during baseflow (not when there is local recharge diluting the flow), it would be a sign of impacts due to fracking. The metals are specific factors that could be change.
- Monitoring should continue for as long as necessary to detect contaminants reaching the springs. The monitoring time required depends on the time to transport along the flow paths.

- Regarding transport from the oil and gas producing formations to shallow groundwater which feeds the springs, monitoring would require centuries.
- Just after hydraulic fracturing, monitoring should occur quarterly so as not to miss a slug of contaminants, but frequency may decrease to annually within a few years, depending upon the estimated travel time from the potential pollution source to the springs.
- Additionally, a recording flow meter should be established at San Solomon Spring, and as many of the springs as possible.

References

Bumgarner JR, Stanton GP, Teeple AP, JV Thomas, Houston NA, Payne JD, Musgrove M (2012) *A conceptual model of the hydrogeologic framework, geochemistry, and groundwater-flow system of the Edwards-Trinity and related aquifers in the Pecos County region, Texas.* US Geological Survey Scientific Investigations Report 2012-5124.

Chesnaux R, dal Soglio L, Wendling G (2013) *Modelling the impacts of shale gas extraction on groundwater and surface water resources.* Presented at GEOMontreal 2013, September 29 – October 3, 2013, Montreal, Quebec

Clark G (2016) Presentation at Johnson Rice Energy Conference. Apache VP Investor Relations.

Chowdhury AH, Ridgeway C, Mace RE (2004) *Origin of the waters in the San Solomon Spring system, Trans-Pecos Texas*, chp 17 in: Mace RE, Angle ES, Mullican WF (eds.) Aquifers of the Edwards Plateau, Texas Water Development Board Report 360.

Clark BR, Bumgarner JR, Houston NA, Foster AL (2014) *Simulation of groundwater flow in the Edwards-Trinity and related aquifers in the Pecos County region, Texas* (ver 1.1, August 2014). US Geological Survey Scientific Investigations Report 2013-5228.

Considine TJ, Watson RW, Considine NB, Martin JP (2013) *Environmental regulation and compliance of Marcellus shale gas drilling.* Environ Geosci 20:1-16

Darrah, T.H, A Vengosh, R.B. Jackson, N.R. Warner, and R.J.Poreda. 2014. *Nobel gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales.* PNAS Early Edition. Doi:10;.1073/pnas.1322107111.

Fairhurst B, Hanson ML, Reid F, Pieracaco N (2012) *Wolfbone play evolution, southern Delaware basin: geologic concept modification that have enhanced economic success.* Search and discovery article #10412. American Association of Petroleum Geologists.

Fontenot BE, Hunt LR, Hildenbrand ZL, Carlton JR DD, Oka H, Walton JL, Hopkins D, Osorio A, Bjorndal B, Hu QH, Schug KA (2013) *An evaluation of water quality in private drinking water wells near natural gas extraction sites in the Barnett shale formation*. Environmental Science Technology 47(17):10032-10040. DOI:10.1021/es4011724.

Frohlich C, DeShon H, Stump B, Hayward C, Hornbach M, Walter JI (2016) *A historical review of induced earthquakes in Texas.* Seismological Research Letters 87(4): 1-17, doi:10.1785/0220160016.

Gassiat CT, Gleeson T, Lefebvre R, McKenzie J (2013) *Hydraulic fracturing in faulted sedimentary basins: Numerical simulation of potential contamination of shallow aquifers over long time scales.* Wat Resour Res 49:8310-8327, doi:10.1002/2013WR014287.

Gross SA, Avens HJ, Banducci AM, Sahmel J, Panko JM, Tvermoes BE (2013) *Analysis of BTEX groundwater concentrations from surface spills associate with hydraulic fracturing operations.* J Air Waste Mgmt Assoc 63(4):424-432, doi:10.1080/10962247.2012.759166.

Hammack, R., W. Harbert, S. Sharma, B. Stewart, R. Capo, A. Wall, A. Wells, R Diehl, D. Blaushild, J. Sams, and G. Veloski. 2014. *An Evaluation of Fracture Growth and Gas/Fluid Migration as Horizontal Marcellus Shale Gas Wells are Hydraulically Fractured in Greene County, Pennsylvania*, NETL-TRS-3-2014, EPAct Technical Report Series. U.S. Department of Energy, National Energy Technology Laboratory. Pittsburgh, PA. 76 p.

Harrison SS (1983) *Evaluating system for ground-water contamination hazards due to gas-well drilling on the glaciated Appalachian Plateau*. Ground Water 21(6):689-701

Howard Weil (2014) *The "New" horizontal Permian basin*. Scotiabank, New Orleans.

Jackson RB, Vengosh A, Darrah TH, Warner NR, Down A, Poreda RJ, Osborn SG, ZhaoK, Karr JD (2013) *Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction.* Proc Natl Acad Sci, USA 110(28):11250-11255

Jiang M, CT Hendrickson, JM VanBriesen (2013) *Life cycle water consumption and wastewater generation impacts of a Marcellus shale gas well.* Environ Sci Technol 48:1911-1920, doi 10.1021/es4047654.

Kharaka YK, Thordsen JJ, Conaway CH, Thomas RB (2013) *The energy-water nexus: potential groundwater-quality degradation associated with production of shale gas.* Procedia Earth and Planetary Science 7:417-422.

Kissinger A, Helmig R, Ebigbo A, Class H, Lange T, Sauter M, Heitfeld M, Klunker J (2013) *Hydraulic fracturing in unconventional gas reservoirs: risks in the geological system, part 2.* Env Earth Sci, doi 10.1007/s12665-013-2578-6

Kondash A, Vengosh A (2015) *Water footprint of hydraulic fracturing.* Enviro Sci Technol Lett 2:276-280. Doi:10.102/acs.estlett.5b00211.

Lange T, Sauter M, Heitfeld M, Schetelig K, Brosig K, Jahnke W, Kissinger A, Helmig R, Ebigbo A, Class H (2013) *Hydraulic fracturing in unconventional gas reservoirs: risks in the geological system part 1.* Environ Earth Sci DOI 10.1007/s12665-013-2803-3.

Llewellyn GT (2014) *Evidence and mechanisms for Appalachian Basin brine migration into shallow aquifers in NE Pennsylvania, USA.* Hydrog J DOI 10.1007/s10040-014-1125-1

Molofsky LJ, Connor JA, Wylie AS, Wagner T, Farhat SK (2013) *Evaluation of methane sources in groundwater in northeastern Pennsylvania.* Groundwater 51(3):333-349, Doi:10.1111/gwat.12056

Myers T (2012) *Potential contaminant pathways from hydraulically fractured shale to aquifers.* Ground Water 50(6): 872-882 doi: 10.1111/j.1745-6584.2012.00933.x

Nicot JP, Scanlon BR (2012) *Water use for shale-gas production in Texas*. U.S. Environ Sci Technol 46:3580-3586. Dx.doi.org/10.1021/es204602t.

Osborn SG, Vengosh A, Warner NR, Jackson RB (2011) *Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing.* Proc Natl Acad Sci, USA 108:8172-8176

Rahm D (2011) *Regulating hydraulic fracturing in shale gas plays: The case of Texas.* Energy Policy 39:2974-2981.

Richey, SF, Wells JG, Stephens KT (1985) *Geohydrology of the Delaware basin and vicinity, Texas and New Mexico.* US Geological Survey Water-Resources Investigations Report 84-4077.

Scanlon BR, Reedy RC, Nicot JP (2014a) *Comparison of water use for hydraulic fracturing for unconventional oil and gas versus conventional oil.* Environ Sci Technol 48:12386-12393.

Scanlon BR, Reedy RC, Nicot JP (2014b) *Will water scarcity in semiarid regions limit hydraulic fracturing of shale plays?* Environ Res Lett 9:124011.

Sellards EH (1932) *The Valentine, Texas Earthquake*. P 113 to 138 in Contributions to Geology, 1932, The University of Texas Bulletin No. 3201.

Sharp Jr JM (2001) *Regional groundwater flow systems in Trans-Pecos Texas*. Chapter 4 in Mace RE, Mullican WF III, Angle ES (eds.) Aquifers of West Texas. Texas Water Development Board, Austin Texas.

Sharp Jr JM, Boghici R, Uliana MM (2003) *Groundwater systems feeding the springs of west Texas.* In: Garrett GP, Allan NL (eds.) Aquatic Fauna of the Northern Chihuahuan Desert: Number 46, 12 May 2003.

Texas Parks and Wildlife (2005) *Diminished Spring Flows in the San Solomon Springs System, Trans-Pecos, Texas*.

Uliana MM, Banner JL, Sharp Jr JM (2007) *Regional groundwater flow paths in Trans-Pecos, Texas inferred from oxygen, hydrogen, and strontium isotopes*. J Hydrol 334:334-346.

U.S. Fish and Wildlife Service (USFWS) (2013) *Comanche Springs Pupfish (Cyprinodon elegans) 5-Year Review: Summary and Evaluation.* Austin Field Office, August 2013.

Vidic RD, Brantley SL, Vandenbossche JM, Yoxtheimer D, Abad JD (2013) *Impact of shale gas development on regional water quality.* Science 340, 1235009 (2013). DOI: 10.1126/science.1235009

Warner NR, Jackson RB, Darrah TH, Osborn SG, Down A, K. Zhao, A. White, A. Vengosh. 2012. *Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania.* Proceedings of the National Academy of Sciences pnas.1121181109

White WN, Gale HS, Nye SS (1941) *Geology and ground-water resources of the Balmorhea area, western Texas,* US Geological Survey Water Supply Paper 849-C.

Zhang, L., N. Anderson, R. Dilmore, D.J. Soeder, and G. Bromhal. 2014. *Leakage detection of Marcellus shale natural gas at an upper Devonian gas monitoring well: A 3-D numerical modeling approach*. Environmental Science and Technology 48:10795-10803, doi:10.1021/es501997p.